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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM

No. 1152

THE SEPARATION OF FLOW DUE TO COMPRESSIBILITY SHOCK

By A. Weise

Translation

"Über die Strömungsablösung durch Verdichtungsstösse"

Technische Berichte Band 10, Heft. 2, 1943, pp. 59 to 61

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SUMMARY

It is known that the compressibility shocks accompanying local or total supersonic flows lead to pronounced flow separations which result in unusually high energy losses on airplane wings, vanes, and in diffusers. The phenomena were investigated experimentally and theoretically. Although the findings have not been completely worked up, some of the observations are presented in the present report.

I. TWO PRINCIPAL FORMS OF FLOW SEPARATION

The compressibility shock proceeding from the region of separation is of necessity oblique, because only it enables a deflection of the supersonic flow at the wall and so the formation of a dead-air region. The dead-air boundary is, at first, straight. The angles between flow direction, on the one hand, and the shock front and dead-air boundary, on the other, stand in the known relationships established in the theory of the oblique compressibility shock. Although all separations in this respect look alike, they result in great differences if the subsequent process of separation shock is taken into account. From the numerous schlieren records of supersonic flows taken throughout the years, two principal types of shock patterns have involved:

(a) The simple curved shock which strikes the wall as an oblique shock continuously changes in direction with increasing distance from the wall and gradually

*"Über die Strömungsablosung durch Verdichtungsstösse, Technische Berichte, Band 10, Heft 2, 1943, pp. 59 to 61.

turns into the vertical shock. This shock manifests comparatively little separation and a marked tendency to close in. (See fig. 1(a).)

(b) The forked or branched compressibility shock, which likewise starts as separating oblique shock at the wall, but then at some distance away from it, branches out under discontinuous change of direction. One branch, the principal shock, which may be vertical or oblique in the junction point, continues straight or curved into the flow. The other branch turns back as oblique shock toward the wall, but terminates, before reaching it, at the boundary of the dead-air region, which in this point has a discontinuity. (See fig. 1(b).) Hence, the term "vertical" or "oblique" branch is employed hereafter, depending upon the character of the principal shock.

II. THEORY OF BRANCHING (OR FORKING)

The theory of the individual oblique or vertical compressibility shock is generally known. The calculation of the branch is based on the conditions resulting from the fact that in the flow from the branching point transverse to the streamlines, no discontinuity in direction or pressure, but only in the velocity may occur. In consequence:

(a) The sum of the deflections in the first and second oblique shock in the branch point must be equal to the deflection in the principal shock.

(b) The product of the pressure ratios in the first and second oblique shock must be equal to the pressure ratio of the principal shock.

The calculation was carried out for parallel inflow with respect to the dimensionless flow velocity $\omega_1 = \frac{w_1}{a_1^*}$ (w_1 = absolute flow velocity, a_1^* = critical velocity). As an important result, it was found that vertical branches or forks occur in air ($\chi = 1.405$) only for $\omega_1 \geqq 1.353$, that is, for Mach numbers $M \geqq 1.484$.[1] Oblique branches are still possible in a certain range below this limit. The angles occurring at the vertical branches, which definitely depend upon the flow velocity, are represented in figure 2, while figure 3 gives the pressures produced by the individual oblique shocks, as well as the total shock in the logarithmic ordinate scale.

For given angle of deflection either a "weak" oblique shock of low pressure or a "strong" oblique shock of higher pressure ratio that leads to subsonic velocity, is possible. At maximum angle of deflection strong and weak shock are identical. At the fork the first oblique shock must always be weak and result in supersonic velocity, or else no second oblique shock is possible. At $1.353 \leqq \omega_1 \leqq 1.75$ the second oblique shock is strong, at $\omega_1 = 1.75$ the deflection is maximum and beyond it is weak. The absolute maximum angle of deflection, which, however, lies below the related maximum, is reached at $\omega_1 = 2.2$. Up to $\omega_1 = 1.8$ the second oblique shock results in subsonic, above it to supersonic velocity.[2]

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[1]The formula reads:

$$\omega_1^2 \geqq \frac{\chi - 1}{\chi + 1} + \frac{\chi - 1}{\chi} + \left(\frac{\chi + 1}{\chi - 1}\,\frac{\chi - 1}{\chi + 1}\right). \quad ?$$

The value varies little with χ.

[2]Double oblique shocks exist also for flow velocities above $\omega_1 = 1.353$, after the passage of which the flow reaches pressures, without resulting deflection, which up to a certain upper limit lie above the terminal pressure of the vertical shocks. Such double oblique shocks can, of course, form no branches (or forks). But they compress with greater efficiency than the vertical shock.

III. CONSEQUENCES OF BRANCHING (OR FORKING)

The schlieren record, figure 4, shows a vertical double branch in a divergent channel. Branches (or forks) having a common vertical principal shock proceed from opposite points of the channel wall. The two slits provided for a removal of boundary layer by suction are unused; they lie in the dead-air region and are therefore inconsequential for the flow.

The photograph, figure 4, shows another significant fact, namely, the appearance of waves downstream from the forks, the practically stationary character of which with regard to a certain fluctuation of the phenomenon was specifically checked and confirmed by slow-motion pictures (frequency up to $3000 s^{-1}$).[3]

This formation of waves is also found on the old schlieren photographs of Laval nozzles (Prandtl) as well as on modern schlieren records of airplane wings. But they are not plain enough to show the nature of the phenomena. Stodola's pressure-distribution measurements in Laval nozzles exhibit periodic pressure variations behind the shock.

The wave formation is at first reminiscent of the familar phenomena accompanying the discharge from divergent or nonconvergent nozzles against high or low pressure. But it is of another kind and especially interesting for the reason that the flow velocity changes periodically between the subsonic and the supersonic range. For behind the vertical principal shock (respectively, for $1.353 \leqq \omega_1 \leqq 1.8$ behind the entire fork) subsonic velocity prevails. From observations of the Mach lines at obstacles, introduced in the wave pattern, it was proved that supersonic speed is reached again. The strong schlieren transverse to the flow following the fork therefore represent developed compressibility shocks, which at least in the center, always lead from

[3] There also occur periodic nonstationary multiple shocks, which in interesting cycle move with velocities of the order of magnitude of the flow velocity.

supersonic to subsonic velocity. Due to the energy consumption of these shocks the phenomenon ultimately dies out, but not as rapidly as the cited pure supersonic waves in gas jets.

According to the observations up to now, the described wave formation seems to be tied to the existence of forks, hence is not present with curved separation shock, which is comprehensible; for the pressure in the dead-air region is also determined by the pressure relation of the first oblique shock. It is lower than the terminal pressure reached by the fork. This cannot be maintained, since the pressure at the dead-air boundary can, at the most, vary slowly, but in no case discontinuously. Thus the compression is immediately followed by an expansion for which a pressure gradient is always available at the dead-air boundary, and which is higher than the critical. (See fig. 3,II(b).) Through the wave formation a part of the flow energy is transformed in vibration energy and ultimately lost mechanically by damping (principally in the shocks). The pressure rise itself achieved by the principal shock does not penetrate as far as the wall. This explains the great flow losses associated with branching. At simple separation without branching the discontinuous compressibility at the dead-air boundary stops and with it the cause of wave formation. The flow pushes through the pressure gradient along the curved shock and ensuing curvature of the streamline is toward the wall - that is, the flow closes into the wall.

IV. PREVENTION OF BRANCHING AND OF SEPARATION OF FLOW

Even in the presence of fairly thin boundary layers, branching was always observed above the computed branch limit, although a simple separation by curved shock would also be conceivable. But by removal of the

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[4]In the channel the principal shock can, of course, occasionally shrink to a point. For very heavy boundary layer, as on rough walls, for instance, the fork can degenerate so that in place of the first oblique shock a fan of compressibility lines emerges from the then curved dead-air boundary.

boundary layer by suction it was possible to secure vertical or curved shocks which reached the wall free from separation. An example is shown in figure 5. The removal by suction through the slits branching from the main channel is connected. Since the main channel behind the suction point is not set off toward the inside, the flow strikes the channel wall back of the slit obliquely. In consequence there is a deflection in wall direction with oblique shock, which curves and up to channel center changes in a vertical shock, perfectly free from separation. For this reason, the only losses are those due to the entropy increase in the shock. The removal by suction further results in a stabilization of the position of the shock.

Translated by J. Vanier
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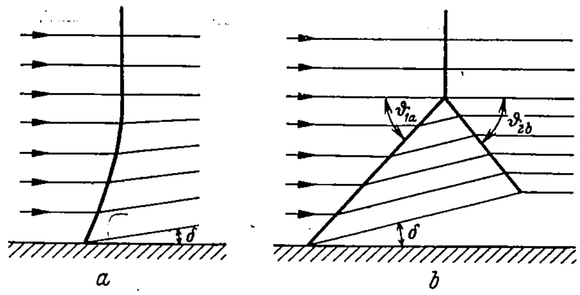

Figure 1.- (a) Diagram of a curved separation shock.
(b) Separation due to "vertical shock fork."

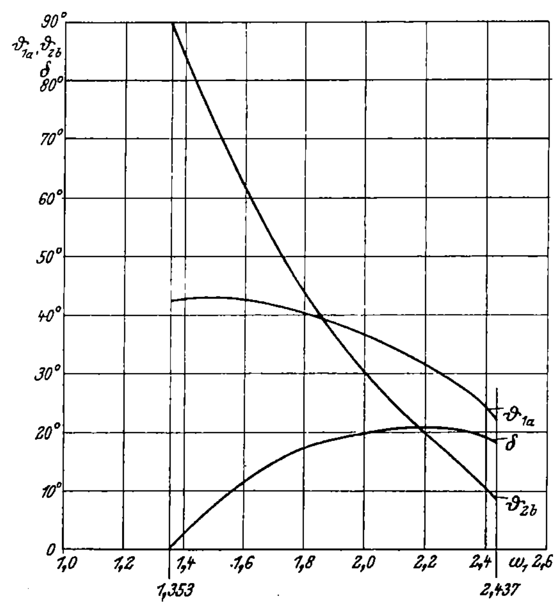

Figure 2.- Angles of the "vertical shock fork" plotted against the dimensionless inflow velocity

$$\omega_1 = \frac{w_1}{a_1^*} .$$ (Identification of angles by figure 1(b).)

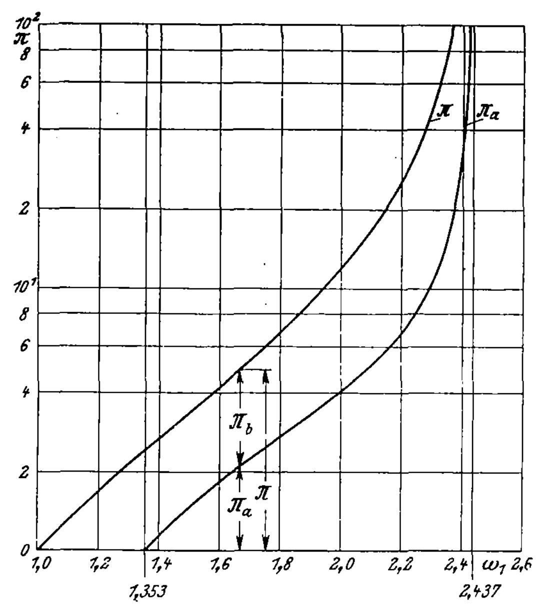

Figure 3.- Pressure relations for the vertical fork plotted against nondimensional flow velocity

$\omega_1 = \frac{w_1}{a_1^*}$, π_a = pressure rati

of the first oblique shock,
π_b = pressure ratio of the

second oblique shock,
π = pressure ratio of vertical shock and of both oblique shocks.

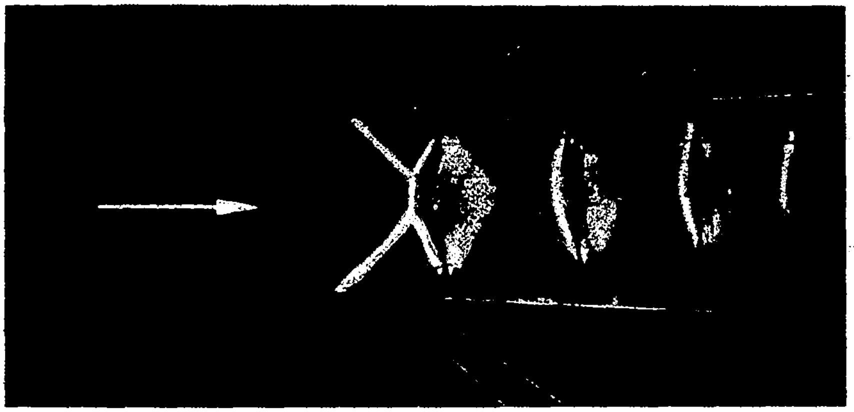

Figure 4. Double fork with separation of flow and formation of waves in a divergent channel. No flow passes through the suction slits. The arrow indicates the direction of flow. The dead air boundary is visible (Schlieren photograph).

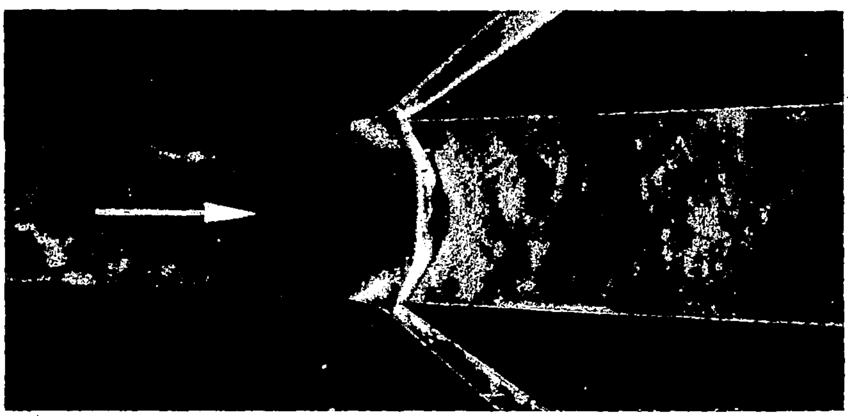

Figure 5. Compressibility shock in a divergent channel free from separation, obtained by boundary layer removal by suction through the two visible slits. The arrow indicates the flow direction (Schlieren photograph).